The ARESA Project: Facilitating Research, Development and Commercialization of WSNs

M. Dohler*, D. Barthel, S. Aubert, C. Dugas, F. Maraninchi, L. Mounier,
A. Buhrig, F. Paugnat, M. Renaudin, A. Duda, M. Heusse and F. Valois

Abstract— **Within academia, wireless sensor networks have witnessed a tremendous upsurge in the last decade, which is mainly attributed to their unprecedented operating conditions and hence unlimited research challenges. Within industry, the projected business opportunities are huge with, e.g. according to Frost & Sullivan, an expected market size of approximately $2b by 2012 at a compound annual growth rate of 41.9%, therefore causing the interest in this technology to augment dramatically. The aim of the ARESA project is to capitalize on this academic and industrial momentum and provide clear and knowledgeable guidelines and solutions related to the research, development and commercialization of this emerging technology. The diverse background of the involved partners facilitates unprecedented insights into the design process from conception to revenue makings. This paper aims at summarizing some key issues one encounters when researching medium access control and routing protocols, formally verifying their proper functioning, developing low-power hardware, and finally commercializing wireless sensor networks.**

I. Introduction

The ARESA project is a French national project with the aim to facilitate research, developments and commercialization of wireless sensor networks (WSNs) and embedded systems. It is comprised of a healthy mix of industrial and academic partners, all of which have a wide range of complementing expertise. The project background and aims, as well as related projects and the partners' involvements are exposed in the following.

M. Dohler and D. Barthel are with France Telecom R&D, 38243 Meylan Cedex, France, {Mischa.Dohler, Dominique.Barthel}@orange-ftgroup.com).

S. Aubert and C. Dugas are with Coronis, 34000 Montpellier, France, {Stephane.Aubert, Christophe.Dugas}@coronis.com.

F. Maraninchi and L. Mounier are with Verimag UJF, 38000 Grenoble, France, {Florence.Maraninchi, Laurent.Mounier}@imag.fr.

A. Buhrig, F. Paugnat and M. Renaudin are with TIMA INPG, 38000 Grenoble, France, {Aurelien.Buhrig, Franck.Paugnat, Marc.Renaudin}@imag.fr.

A. Duda and M. Heusse are with IMAG INPG, 38000 Grenoble, France, {Andrzej.Duda, Martin.Heusse}@imag.fr.

F. Valois is with CITI INSA, 69000 Lyon, France, Fabrice.Valois@insa-lyon.fr.

A. Background

Sensor networks have been researched and deployed for decades already; their wireless extension, however, has witnessed a tremendous upsurge in recent years. This is mainly attributed to the unprecedented operating conditions of WSNs, i.e. a potentially enormous amount of sensor nodes reliably operating under stringent energy constraints.

WSNs allow for an untethered sensing of the environment. It is anticipated that within a few years, sensors will be deployed in a variety of scenarios, ranging from environmental monitoring to health care, from the public to the private sector, etc. They will be battery-driven and deployed in great numbers in an ad hoc fashion, requiring communication protocols and embedded system components to run in an utmost energy efficient manner.

Prior to large-scale deployment, however, a gamut of problems has still to be solved which relates to various issues, such as the extraction of application scenarios, design of suitable software and hardware architectures, development of communication and organization protocols, validation and first steps of prototyping, until the actual commercialization.

B. Related Projects

Numerous past, current and emerging projects worldwide focus on a subset of above mentioned problems, so as to facilitate a successful deployment of WSNs. A non-exhaustive but related set of international projects – along with the projects' main goals – is summarized below.

E-Sense: The aim of the E-Sense project is to capture ambient intelligence through WSNs by means of interaction between body sensor networks, object sensor networks and environmental sensor networks.

CRUISE: It is a European Network of Excellence (NoE), which deals with a wide range of scenarios and applications of WSNs.

Bridges: The Sustainable Bridges project aims at developing a reliable and cost-effective solution for detecting structural defects in bridges. The technology also allows for the estimation of the remaining lifetime of the bridges.

SDIC: It stands for Smart Dust Inventory Control, which allows the exact tracking of your products - from the packaging to the truck carrying the palettes.

Car Control: The Cortex's car control project automatically finds you the optimum route to the destination, where various sensor readings are included in the calculation; for instance, traffic, weather, constructions, jam reporting, etc.

GlacsWeb: This project monitors the drifting behavior of glaciers by aggregating pressure, movement and temperature data collected by sensors on top and within the glacier.

SMWF: It stands for Smart Mesh Weather Forecasting and is deployed in the Yosemite National Park. Various factors are measured, analyzed and predicted over the years, relating, for instance, to snowmelt.

MyHeart: Sensors measure variables impacting upon cardio-vascular diseases, thereby facilitating an early diagnosis. The system extends beyond the measurements of body internal variables, such as blood sugar level, pressure, etc; lifestyle factors ranging from choice of clothes, environment, etc., are also considered to draw preventive conclusions.

WiSeNts: It is an EU IST FP6 project with the aims to develop a new research domain, integrating the broad context of embedded systems with ubiquitous computing and wireless sensor networks in support of Cooperating Objects. They are integrating existing research in the field and related fields and developing a technology roadmap to drive the vision forward.

These projects are usually furnished by a large and knowledgeable partnership. The interests and backgrounds of participating partners, however, are usually fairly correlated and homogenous.

C. ARESA's Project Aims

The ARESA project had been assembled keeping in mind that designing a highly-efficient WSN is a cross-community exercise. Therefore, in contrast to above-mentioned projects, the ARESA project is constituted of partners with a fairly complementary expertise with the aim to:

- explore new event-driven and asynchronous software and hardware architectures, tailored to extremely low power consumptions;
- propose new communication and organization protocols, which are optimized in terms of energy consumption and robustness;
- study new network structures which facilitate auto-configuration and auto-organization;
- find new application protocols that are designed for data fusion and aggregation;
- provide tools of modeling and validation, which also take into account the physical environment and the interaction thereof with the wireless sensor nodes; and
- validate the developed concepts, protocols and mechanisms by means of a testbed.

It is the aim of the ARESA consortium to propose an integrated industrial and applicative solution in the emerging area of wireless sensor networks. We wish to knowledgably influence the design of potentially to-be-standardized communication protocols for energy-constrained wireless sensor networks, which, we believe, form the basis of ambient data processing and communication systems.

D. Project Partners

To achieve these goals, a healthy mix of industrial and academic partners has been assembled with a strong track record in sensor and embedded communication systems. The industrial partners are comprised of France Telecom R&D, which has a leading expertise in ambient systems and wireless sensor network design, and CORONIS Systems, which are a European leader in sensor networks with invaluable real-world roll-out experiences. The academic partners, on the other hand, are constituted of the research centers LSR/INPG, CITI/INSA Lyon, VERIMAG/UJF and TIMA/INPG.

The **France Telecom Group** constitutes one of the biggest integrated operators worldwide. It offers a variety of services to its clientele, including mobile and fixed telephony, wired and wireless internet, as well as integrated home and business solutions. Through wireless sensor networks (WSNs), it hopes to offer more complete services by creating and facilitating ambient environments, which interface with incumbent and emerging services. For this reason, France Telecom has strong R&D activities in the area of WSNs - corroborated by the leadership of the ARESA project. The expertise of France Telecom is on the inputs of commercially viable sensor scenarios, design of low-power physical (PHY) and medium access control (MAC) layers, routing protocols, as well as cross-layer optimized communication mechanisms.

Coronis provides solutions for ultra-low-power (ULP) and long-range wireless applications. The company is the creator of Wavenis®, a technology core for its radio frequency (RF) transceiver and wireless communication protocol. With Wavenis, Coronis offers a complete line of wireless platforms for original equipment manufacturers (OEMs), meeting technical, operational, and cost requirements of ultra-low-powered wireless mesh sensor networks. Major markets for Coronis technology are remote utility meter monitoring, home comfort, alarms for protecting people and property, home healthcare, industrial automation, centralized building management, access control, temperature monitoring, as well as long-range UHF RFID applications for the identification, tracking, and locating people and objects. Over 1 million devices made with Wavenis will be deployed by the end of 2006. The expertise of Coronis hence lays on development and commercialization, as well as real-world protocol design.

LSR/INPG has worked for years on issues related to MAC and routing for WSNs. In particular, their work relates to routing protocols in dense energy-constrained networks. The laboratory has also strong competences on wireless local area networks and ad hoc networks. Their main implication within ARESA is to design suitable protocols, which are tailored to extracted application scenarios and implementable into the developed hardware.

CITI/INSA, whilst also having a strong expertise in MAC, their implication in ARESA is on auto-organization and auto-configuration mechanisms for energy-constrained WSNs. Their research includes theoretical studies and modeling, where developed solutions will have to fit neatly with developed routing protocols.

VERIMAG/UJF is specialized in methods and tools for the development of safe and efficient embedded systems, ranging from embedded control to communication protocols. Their prime role in ARESA is to develop and analyze a formal model of a sensor network's behavior. This model should be accurate enough to estimate the energy consumption, and it should include the hardware, the application software, the protocols, and the physical environment. Such a modeling approach uses formal languages for reactive systems that have proven both efficiently executable and formally analyzable in a wide variety of embedded contexts.

TIMA/INPG is specialized in the design and the integration of autonomous wireless sensor systems. It has strong competencies in the methodology of designing hardware systems, in the field of the energy harvesting and in the field of systems very low fuel consumption. Their implications within ARESA are mainly related to optimizing the power consumption of asynchronous and event-driven hardware architectures, i.e. the algorithms developed and verified by the other partners will be realized and optimized for their hardware.

The complementary expertise of the involved partners gives ARESA the much needed synergy to facilitate application-oriented research, development and commercialization.

II. Most Challenging Research Problems

The research challenges listed in this section are the result of Coronis' experiences obtained during the roll-out of the world-wide first commercial wireless sensor meter-reading service in the South of France. Almost one Million nodes are now operational, giving Coronis the knowledge on pertinent deployment problems. Resulting research challenges and associated problems are listed below.

A. Design Drivers

To accelerate roll-outs, the WSN ought to be decentralized, i.e. have no central point of control prior to deployment. This behavior is well studied within ad hoc networks and derived conclusions and insights can hence be utilized. Also, the information flow within WSNs is usually highly directed, i.e. from a large set of sensors towards a few data-collecting processing units. This behavior is contrasting a typical ad hoc network data flow, however, is well studied within traditional and multihop cellular communication systems. Finally, just as in any incumbent system, WSNs need to exhibit robustness (reliable delivery of data), integrity (correct delivery of data), and confidentiality (secure delivery of data); among several other requirements.

In contrast to known and well understood systems, however, a WSN bears also some fundamental design differences. These are summarized below.

Number of Nodes: The number of nodes involved is very large, where current rollout examples include a few thousands; however, roll-out expectations are in the range of a few hundred thousand nodes communicating simultaneously. This is also atypical any wireless system today.

Energy: WSNs are nowadays battery powered and, because changing batteries in a few thousand nodes on a regular basis is clearly impractical, they are required to have a long lifetime and are hence considered to be highly constrained in energy. This is in contrast to any deployed wireless system, where nodes are usually either powered by the mains or rechargeable on a regular basis.

Applications: The gamut of applications is vast, hence requiring very different solutions to be developed for different applications. This problem is further enhanced due to the stringent energy constraints, requiring subtle solutions to be developed for different requirements.

This means that, unlike incumbent systems, our WSNs need to be:

- highly scalable (protocols ought to work at arbitrary number of nodes);

- highly energy efficient (at all layers and functionalities); and
- highly application tailored (efficient for a given task).

To achieve this, we shall subsequently look at some fundamental trade-offs and research challenges.

B. Impact of Scaling Laws

The first question posed by the consortium was on the issue of scalability of WSNs, i.e. when a network has to be considered large. To exemplify this problem, we have presupposed systems with and without internal conflicts. For instance, two systems without conflicts are our circle of true friends (comprised by a small number of elements) and the soldiers of an ant colony (comprised by a small number of elements). On the other hand, two systems with conflicts, frictions and competition are, for example, a few children left on their own (comprised by a small number of elements) and state without government (comprised by a small number of elements). As such, 'large' is hence not about size. It is rather about managing existing and emerging conflicts, and hence the amount of overheads needed to facilitate (fair) communication.

A management of conflicts is facilitated by a centralized entity, as for instance a base station in a cellular system. WSNs, however, do not have centralized entities prior to their deployment. This leads to scalability problems, as quantified below.

Kumar & Gupta's Throughput Scaling Law. This milestone contribution [1] quantifies the theoretically achievable network capacity assuming that everybody talks with everybody. They have determined that, assuming random deployment of N nodes in a large network, the throughput scales proportionally to $1/\sqrt{N \log N}$. The throughput hence decreases rapidly with an increasing number of nodes. In other words, no matter what we try, we cannot design a scalable protocol for large networks and hence topologies different from pure ad hoc have to be invoked.

Odlyzko & Tilly's Value Scaling Law. Mainly economically driven, various efforts in the past have been dedicated to establishing the value of a network in dependency of the number of its elements N. Sarnoff's Law quantifies the value of a broadcast network to be proportional to N [2]. Reed's Law claims that with N members you can form communities in 2^N possible ways; the value hence scales with 2^N [3]. Matcalfe's Law, unjustifiably blamed for many dot-com crashes, claims that N members can have $N(N-1)$ communication connections; the value of the network hence scales with N^2.

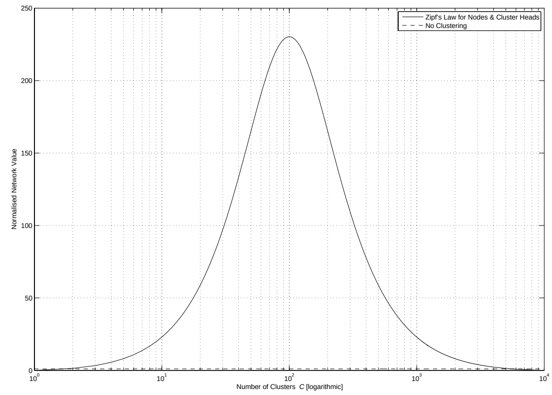

Fig. 1. Normalized network value with different clustering approaches.

Since a WSN is not truly of broadcast nature, nor do sensors form all possible communities, nor does every sensor communicate with every other sensor, another value scaling law is required to quantify the network's behavior. To this end, Odlyzko and Tilly have proposed a value scaling which is proportional to $N \log N$ [5]. Their argumentation bases on Zipf's Law [6], which states that if one orders a large collection of entities by size or popularity, the entity ranked k-th, will be about $1/k$ of the first one. The added value of a node to talk to the remaining nodes is hence $1 + 1/2 + 1/3 + \cdots + 1/(N-1) \propto \log N$; the value of the total network with N members hence scales with $N \log N$. Among others, this law has been found to describe accurately the merging and partitioning of companies of unequal size [5].

Using Odlyzko and Tilly's value scaling law, we wish to determine a clustering of a large WSN such that its value is maximized. With N nodes in the total network and C clusters, we have $M = N/C$ nodes per cluster. Assuming that the value of the nodes within a cluster as well as the cluster heads obeys Zipf's Law, the value per cluster is $M \log M$ and the value of the clustered network is $C \log C \cdot M \log M$. We shall normalize this value by the average number of links needed to maintain all nodes and clusters at any time, which is $C \log C \cdot +M \log M$. The relative network value for different cluster sizes is depicted in Figure 1 with $N = 10,000$ nodes. Clearly, clustering increases the normalized network value. For instance, if we assume a WSN with $10,000$ nodes and a directed information transmission among nodes to the cluster heads and among cluster heads towards the information sink, an optimal cluster number is 100 with about 100 nodes per cluster. For $N = 1000$, the optimal cluster number would about 12, etc.

Practical Hierarchical Scaling Law. This simple law quantifies the network throughput for practical systems with a given topology and gives insights into the design of data pipes between nodes. Among many possible topologies, we assume that each node communicates only with its respective cluster head and all cluster heads communicate among each other.

We hence assume a 2-tier hierarchy with N total nodes, C clusters and $M = N/C$ nodes per cluster. As before, this 2-tier hierarchy requires two communication phases. In the first phase, all nodes communicate with their respective cluster-heads, and in the second phase, all cluster-heads communicate among each other. For subsequent analysis, we first assume all data pipes to have equal rates and then extend this to unequal pipes.

For equal data pipes, in the first phase, there shall be M time slots to transmit $c \cdot N$ bits, where c is a constant assumed to be one. In the second phase, there are hence $M \cdot C \cdot (C-1)$ time slots to transmit these N bits to every cluster head. The efficiency is hence $N/(M \cdot C \cdot (C-1))$; remember that no new information is injected in the second phase.

For unequal data pipes, let us assume the cluster-heads' pipes to be r times stronger than the data pipes between nodes towards the cluster heads. Therefore, in the first phase, there are again M time slots to transmit N bits; and in the second phase there are now $M \cdot C \cdot (C-1)/r$ time slots to transmit these N bits. The efficiency is hence $N/(M \cdot C \cdot (C-1)/r)$.

The relative network throughput for different cluster sizes is depicted in Figure 2 with $N = 10,000$ nodes. Clearly, clustering increases the normalized network throughput only if the data pipes among the cluster heads are stronger or data aggregation [7] is performed to decimate the information shared among cluster heads. For instance, if we assume a WSN with $10,000$ nodes, then an optimal cluster number is 12 assuming the cluster heads' data pipes to be 1000 times stronger. If not all cluster heads communicated, as in the previous example, then the optimal cluster number would be larger.

Above quantification of throughput and value of a large WSN hence stipulate the use of clustered approaches. This is corroborated by real-world roll-outs, all of which use hierarchical and/or clustered network topologies with stronger data pipes between cluster heads. For example, the currently functioning meter reading application of Coronis uses a hierarchical approach [8] (see also Figure 3) and so does Intel's WSN. The challenge is hence to design self-organizing protocols for the intra and inter cluster communication topologies. Parts of this shall briefly be discussed subsequently.

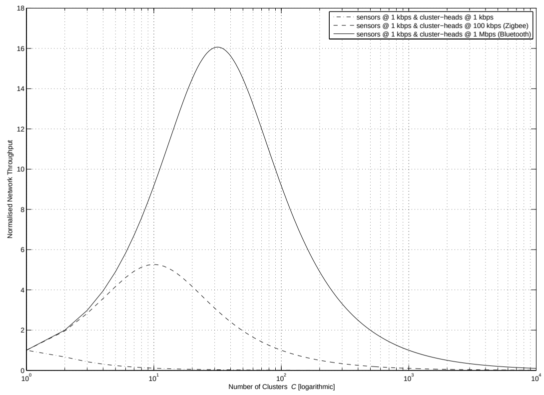

Fig. 2. Normalized network value with different clustering approaches.

C. MAC & Routing Protocols

Once deployed, wireless sensor networks are supposed to convey information from sensor nodes to sinks. This task should be carried out for the longest time possible given a fixed amount of initial energy at the sensors. Therefore, forwarding information in the network must be done according to the remaining energy of the nodes along the chosen paths. Dynamic routing, in which paths depend on the state of the network links, or adaptive routing that operates on finer-grain metrics, need to be adapted so that they not only reach a satisfactory solution, but also they do so at a controlled cost in terms of transmissions.

It is not also not apparent why routing needs to be dynamic in wireless sensor networks. In fact, routing can be computed at the network deployment, but then, any failure of nodes close to the sink, which are inherently more loaded than others, may cause the entire sets of sensors to become isolated. Early failure detection and reverting to backup paths is an immediate improvement and we believe that an autonomous routing protocol can provide a satisfactory solution.

Routing in wireless sensor networks may also benefit from new addressing schemes based on virtual coordinates. If a set of sensors is organized in such a way that their addresses correspond to coordinates in a virtual space, routing is straightforward and does not require any overhead nor signaling traffic for constructing routing tables. Information forwarding just consists of sending packets towards the coordinates of a given destination. Obviously such an approach needs to take into account disappearing nodes, but signaling traffic is in this case only needed to repair or reconstruct the addressing space after some node failures.

Moreover, such an approach can support organizing nodes in a logical way so that a high level querying of nodes will be made possible. For instance, we can explore a content-based approach for forwarding information within a wireless sensor network in which routing is done based on some attributes and not on addresses.

Furthermore, the routing problem is closely related to the way the MAC layer operates. For instance, the relative cost of broadcast transmissions compared to unicast transmissions influences the main design choices for the routing protocol. Conversely, lowering transmission costs is more or less crucial depending on the routing involved.

D. Self-Organization & Self-Healing

Because wireless sensors networks suffer from a random deployment with the least possible human intervention, self-'mechanisms' ought to be provided, such as self-configuration, self-organization, self-healing, etc. Self-configuration allows autonomous nodes configuration in order to set up communication. We commence by assuming that each node owns a unique identity; thus we are not focused on self-configuration [9].

The self-organization paradigm deals with an emergent behavior coming from local nodes interactions [10] and leading to a logical view of the network. The goal of such logical view is to structure the whole network in order to provide more efficient communication protocols (routing or data dissemination). In our point of view, an emergent behavior can be a connected structure as a virtual backbone or non connected one as clusters [11]. The literature has provided intensive works in the area of distributed algorithms in order to structure the network: Connected Dominating Set, Maximum Independent Set, Local Minimum Spanning Tree, Relative Neighborhood Graph, Max-Min clusters, etc. Nevertheless, part of these works are focused only on virtual topology construction without consideration for a maintenance procedure in order to maintain this structure connected. Because of power-energy saving mechanisms or network dynamics the topology evolve. Thus, an event-driven maintenance algorithm should be provided, which out to be the goal of self-healing.

Another goal of self-organization is to build a framework to enable more efficient routing protocols, data aggregation mechanism, etc. Taking into account the applications coming from Coronis and France Telecom R&D, we deem important to specify a self-* architecture in order to build autonomously a logical structure with dedicated applications, such as data dissemination and data aggregation with self-healing mechanisms in order to be able to deal with network dynamics.

III. Prototyping and Development

A strength of the ARESA consortium is that the researched protocols are directly fed into development efforts, as described below.

A. Virtual Prototyping and Formal Analysis

Design Issues for Sensor Networks. A sensor network may be considered as a whole, as a new kind of computer system dedicated to one particular application. It is an *embedded* system, reacting to the stimuli of some physical environment. It is also subject to the usual constraints of embedded system design: resources are scarce, and it is very difficult, if not impossible, to modify a sensor network's behavior once it has been deployed. Moreover, the sensors are usually powered by a battery that cannot be recharged. They should therefore have the lowest consumption possible to maximize the network lifetime.

Several issues may be considered for the design of sensor networks, among which:

- How to *program* the network? For example, knowing that the ultimate goal of the network is to detect a fire, how to design the application code for each node?
- How to take security constraints into account? Indeed, a sensor network is probably very easy to attack.
- How to perform energy-aware design?

In ARESA, we are mainly interested in the last point. The problem is difficult because all the elements of a sensor network have an influence on energy consumption: the hardware of a node, the sensors, the medium-access-control and routing protocols, the application itself, the initial self-organization phase, and even the physical environment that stimulates the sensors (see, for instance [12], where we showed that a precise modeling of the physical environment is compulsory for a realistic estimation of the energy consumption).

The design of an energy-"optimal" solution is probably out of reach because of all the interacting criteria, and the complexity of some of the elements that have to be taken into account. If there is no way to compute an optimal solution, then the only available method seems to build complete solutions and then to evaluate them. However, since a sensor network includes dedicated hardware, it may be long and costly to build a complete solution before evaluating it.

Virtual Prototyping Approaches. For all these reasons, the usual approach is to build a *virtual prototype* of a sensor network, and then to perform simulations or mathematical analyzes in order to evaluate the energy consumption. This is the approach taken by people who design new protocols, and show their benefits using a network simulator. In all these approaches, a lot of *abstractions* are necessary, in order to build manageable models of very large systems (thousands of nodes). For instance, the energy consumption may be evaluated by counting packets, and associating a worst-case estimated energy with the transmission of one individual packet.

However, there seems to be a wide agreement on the fact that traditional network simulators like NS are not sufficient for ad-hoc sensor networks. In particular, they cannot be used to describe the hardware in an accurate way, which seems compulsory for power analyzes. A lot of approaches have been proposed for simulating ad-hoc sensor networks in a both accurate and efficient way. None of these approaches is formalized. Libraries have been developed for some reusable elements of the models, like the protocols, but it is still hard to obtain an accurate and efficient simulator while preserving the faithfulness of the model. Moreover, those simulators do not help in modeling the *environment* of the network, i.e., the physical phenomena that have some influence on the sensors. Finally, as soon as the power analysis needs an accurate simulation of the hardware of a node, the problem becomes the same as simulating efficiently a large piece of hardware. Simulating 1000 nodes at the Register-Transfer-Level (RTL) is probably hopeless. People in the hardware design domain have tackled this problem by defining new levels of abstraction (like the so-called "*transaction-level modeling*" [13]) that are both accurate enough for a first approximate timing or power analysis, and fast to simulate. Developing such an approach for ad-hoc sensor networks requires a clear understanding of the abstractions than can be made on their behavior, while retaining their main power characteristics.

Formal Virtual Prototypes. In ARESA, we address the following challenge: we aim at developing accurate prototypes of sensor networks, that can also be *formally analyzed*. What does it mean? Consider a property related to the lifetime of a sensor network, for instance: "*is this possible to spend more than the energy E in a time period less than T?*". This property can be *tested* on a lot of simulations, and we may find a scenario that indeed spends more than E in less than T. If we do not, however, it does not mean that there exists no such scenario. It may well be the case that we did not try a particularly complex scenario that exhausts all the nodes within a very short time. The aim of formal validation is to give exhaustive answers to such questions, for instance by exploring a mathematical structure that represents all the possible behaviors of the system.

However, automatic formal validation usually faces two major problems: first, the mathematical structure to be explored may be huge; this is called state-explosion, and this is mainly due to the fact that representing the behavior of a parallel system amounts to considering all the states in the Cartesian product of the states of the parallel activities. Even if a node has only two states of interest, a 1000-nodes sensor network has 2^{1000} potential states. Second, even if the size of the model is manageable, it may be the case that the properties we want to assess are *undecidable*. In other words, there exists no algorithm able to answer the question. It happens as soon as one includes general computations on numbers in the model, and it is likely to be the case when modeling the energy consumption of a sensor network.

To address these two problems, one needs either human interaction, or aggressive abstractions. In ARESA, we favor automatic techniques and tools, hence we are interested in the development of abstract models. What does it mean for a model to be abstract? First, since the exact behavior of a sensor network depends on the physical environment, no model or prototype can be exact with respect to energy consumption; all models are bound to make some hypothesis on the physical environment. For evaluating energy consumption, we should develop worst-case models. For instance, the radio can be modeled by considering several states depending on the emission power. A worst-case consumption is then associated with each state.

For the virtual prototype to be trusted, all the worst-case abstractions have to be well-understood and well-identified in a global model. This is why we think that a formal model should be organized into *components*, in such a way that replacing a component C in a global model M by a more abstract version C' yields a new global model M' which is indeed more abstract than M. This abstraction preservation property is essential when playing with various abstractions of the individual components. We should also be able to prove the property: C' is more abstract than C, i.e., that the power estimations computed with C' are always greater than that of C.

Prototyping Challenges. To summarize, the challenges we exposed related to the development of virtual prototypes of sensor networks are as follows:

- The prototype should include all the elements that determine energy consumption: node hardware, protocols, application code, and physical environment.
- The prototype should be executable, so as to allow efficient simulations
- The prototype should be described in a formally-defined language, so as to be analyzable by automatic tools

- The prototype should be made of well-defined components, so as to allow modular abstractions as defined above.

We will use techniques and tools developed at VERIMAG, and which have proven useful in other domains of embedded system design, ranging from embedded control to communication protocols. In particular, the modeling and verification of various embedded reactive systems has led to the design of a formal modeling language for physical environments, which is well adapted to sensor networks. We plan to develop several forms of formal models, depending on the properties to be proved. For instance, the details of a node are best described in some synchronous formalism, while the way several nodes behave together is best described with some asynchronous formalism. We will also use the new application domain of sensor networks to make our tools evolve.

B. Hardware Implementation

As mentioned in the previous section, it is important to tackle the power consumption issue at hardware level in order to increase the WSNs' lifetime. In traditional synchronous design, computations are sequenced by a clock that is connected to every digital hardware blocks which perform calculations at each rising edge, even if no valid data are present. Although some techniques, such as clock gating, exist to reduce activity of such circuits, lots of unneeded signal transitions remain.

In asynchronous QDI technology [14], the parts of the circuit that are performing an operation have an activity. The rest of the circuit consumes very little energy (only static leakage) and are immediately woken-up when an event occurs on its inputs. Synchronization between blocks is performed by requests and acknowledgements.TIMA's asynchronous circuits are delay insensitive (functional correctness independent on gates and wires delays). Therefore, they are very robust to voltage changes and are particularly suited for dynamic voltage scaling (DVS) and can support very low voltages since signal rise and fall times does not affect the correctness.

The DVS technique is an efficient way for reducing power consumption. As the energy consumed is proportional to the square of the voltage, reducing a little the supply voltage decreases a little the speed of the hardware (including the microcontroller) and allows important energy savings at the same time [15], [16]. As a result, we have experienced that for an asynchronous AES crypto-processor (130nm), reducing the computation speed by a factor 2 reduces energy consumption by a factor 9 [17].

To exploit the benefits of asynchronous circuits and to have very low software overheads, TinyOS 2.0 and an appropriate scheduler are considered to apply a power consumption policy that should fit the application requirements at best.

The goal of our work is to efficiently combine TinyOS and asynchronous circuits by, first, supporting hardware tasks within the programming model of TinyOS at quasi no cost in terms of energy and timing overheads; and, second, defining an appropriate scheduler and regulation mechanism that will apply a power consumption/speed policy that should fit the application requirements at best.

C. Product Development

Coronis' real-world meter-reading application [8] requires solutions with least possible power consumption. To this end, Coronis' devices are equipment by a single lithium battery running on 2.7Ah. Because of leakage, the passivation effect, and internal resistance, the actual usage, however, is limited to only 1.6Ah over 10 years. This yields an average consumption of 18μA over 10 years.

Further elaborating on the hardware design approach mentioned in the previous section, higher energy savings can be achieved if the synchronization procedures in the meter-reading products are optimized. To this end, it is important to remember that when a sensor network has to operate for several years, device synchronization cannot be maintained continuously. If synchronization is lost in a synchronized network, devices try to re-establish synchronization by entering into high power consumption mode, thereby shortening the network's lifespan. One solution is for devices to synchronize only when necessary, with communication between devices backed down immediately afterwards. Synchronization can then be performed at predetermined times depending on the application; for instance, one second latency for meter-reading. Application devices hence toggle sequentially between receive mode and standby mode for most of their lives.

It is also possible to extend range by reducing the bandwidth, while keeping the average operating consumption at an ultra low 15μA [8]. New algorithms, tailored to these needs and requirements, are hence key to automatically configuring and managing nodes. As corroborated by currently running applications and briefly elaborated upon in the next section, routing and remote access functionality can be maintained without sacrificing neither technical goals nor key marketing requirements.

IV. Being the First in the Market

Being the first in the market meant to identify potential markets first, where we have distinguished between:

- governmentally support market;
- mass market;
- specialized market; and
- niche market.

Governmental support is usually granted for applications which facilitate the health and security of its citizens. Money and deployment costs are usually not of prime interest. The technological solutions are often required to be robust, reliable and secure, but not necessarily optimum and efficient. For instance, a WSN deployed in border surveillance must be secure and reliable, but may have access to a wide frequency spectrum.

Mass markets are constituted by a non-negligible part of the population. That generally includes the human population, but – in the case of WSNs – may very well extend to the entire flora and fauna. Technological solutions need to be cheap and to a certain degree secure and reliable. The deployment and usage cycle of mass market products rarely exceeds half a dozen of years.

Specialized markets are application and need tailored markets, where a special solution might be applicable to a specific problem. Specialized markets infer high revenues, but not necessarily size. For example, monitoring the growth of grapes is a specialized market, however, with potentially large revenues. The technological requirements are usually very diverse and vary from application to application.

Niche markets address needs which are very specialized and small in size, but – if WSNs are deployed in these markets – life can be made easier and some savings achieved. For instance, the measurement of wind speed for households which use private wind turbines to generated energy. The technological requirements here are also very diverse and vary from application to application.

In Table I, a classification of these markets against typical application domains is given. It is clearly visible that the majority of applications will be in the specialized market, i.e. requiring application-tailored solutions. With this in mind, the market requirements of one of Coronis' commercial products are discussed from a technical point of view.

By operating in the 2.4GHz, 868−870MHz, and 902−928MHz bands (like the recent ZigBee proposal), wireless technologies continue to allow critical equipment to use the less crowded and more regulated 868MHz and 915MHz bands when participating in regular Bluetooth piconets. Coronis' approach is to connect ultra-low power devices to the outside world without defining another standard in the crowded 2.4GHz band. The real challenge is to devise a solution that keeps networks manageable, while offering both longer range and far lower power consumption. Gaussian frequency shift keying modulation, frequency-hopping, hop rate, and timing in the commercial solution are identical to those for Bluetooth, but the data rate has been reduced. Furthermore, as discussed above, synchronization has been adapted to match the requirements of stringent energy constraints.

TABLE I

Taxonomy of application domain versus market type.

	govern.	mass	special.	niche
home, office		✓	✓	
control, automation			✓	✓
logistics, transport	✓		✓	
environm. monitoring	✓	✓		
healthcare	✓	✓	✓	
security	✓		✓	
tourism, leisure			✓	✓
education, training			✓	✓
entertainment		✓		

With these high level technical requirements, Coronis were the first to provide a commercially viable meter-reading solution. The toughest bit about evaluating the feasibility of this new technology has been to see how it actually performed in the field. To this end, 25,000 water meter-reading nodes were installed in the South of France, which constitutes a fully operational automated network capable of gathering water consumption data via a wireless mesh network and transmitting it back to the home office. It is the first large-scale remote-controllable, fixed wireless network of its type in Europe.

With this technology, not only cost-effective solutions for the utility company have been provided, but remote monitoring actually offers many advantages for water customers as well, such as accurate billing and increased meter security. The current customers can even check their usage via Internet and even receive alerts via mobile or pager regarding abnormal consumption patterns such as those caused by leaks. The topology of this commercial application is depicted in Figure 3

Novel applications are currently being envisaged, ranging from environmental monitoring to health care applications. For these applications, research from ARESA will feed directly into the optimization of the data flows, handling of node failure and optimizing the network's lifetime. The proposed solutions are then verified by means of formal methods, so as to ensure 100%

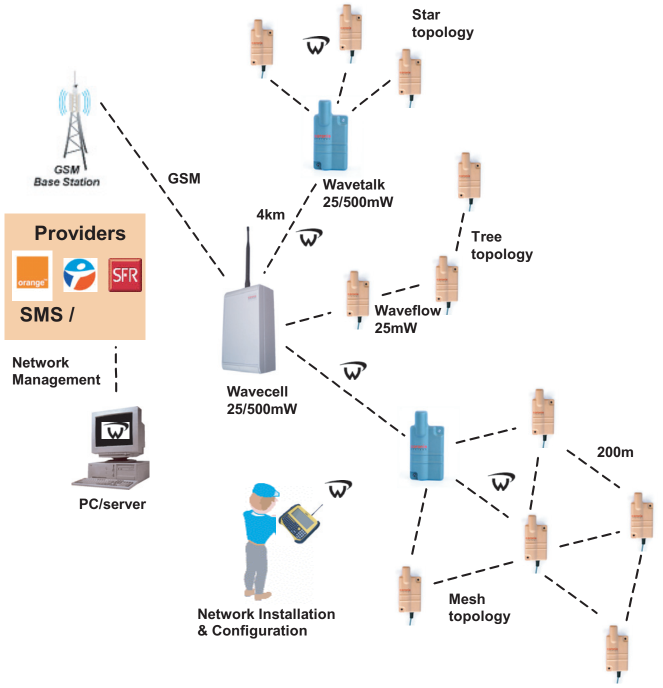

Fig. 3. An optimal topology is automatically configured for each local group in a large-scale ultra-low power network.

reliability under all conceivable operating conditions. These algorithms are then optimized in terms of hardware and energy consumption, which finally facilitates the development of commercially viable products and shortens the crucial time-to-market.

V. Concluding Remarks

The aim of this paper was to expose some crucial issues related to the research, development and commercialization of wireless sensor networks. The coherent insights given here stem from the diverse background of the partners involved in the ARESA project. We have looked at the impact of clustering on the maintenance of a large-scale wireless sensor network, where node numbers are often in the thousands. Using some known scaling laws, we have determined that scalable protocols for flat sensor network topologies cannot exist and that clustering or hierarchical approaches ought to be used instead. We have also identified some approaches which may be useful in determining an optimum cluster size. Thereafter, we have identified crucial research problems at medium access control and routing levels, as well as related to auto-organization and self-healing mechanisms. The concept of virtual prototyping has then been introduced – a tool which proves to be very useful in evaluating the reliability of designed protocols. Furthermore, various hardware issues have been identified which require highest attention if energy consumption was to be minimized. Finally, some market and commercial insights have been given and it has been identified that research and development need to be closely coupled so as to shorten time-to-market for novel wireless sensor networks technologies. We hope that these insights are of significance for emerging and future real-world installations, such as data collection, remote control solutions, wireless telemetry, automatic monitoring, metering solutions and smart environments such as homes, hospitals, and buildings of all kinds.

References

[1] P. Gupta, P.R. Kumar, “Towards an Information Theory of Large Networks: An Achievable Rate Region,” *IEEE Trans. on Inform. Theory*, vol. 49, pp. 1877-1894, August 2003.

[2] K.M. Bilby, *The General: David Sarnoff and the Rise of the Communications Industry*, New York: Harper & Row, 1986.

[3] D.P. Reed, “Weapon of math destruction: A simple formula explains why the Internet is wreaking havoc on business models,” *Context Magazine*, Spring 1999.

[4] G. Gilder, “Metcalfe’s Law and Legacy,” *Forbes ASAP*, 1993.

[5] B. Briscoe, A. Odlyzko, B. Tilly, “Metcalfe’s Law is Wrong,” *IEEE Spectrum Magazine*, July 2006.

[6] G.K. Zipf, “Some determinants of the circulation of information,” *Amer. J. Psychology*, vol 59, 1946, pp. 401-421.

[7] H. Chen, H. Mineno, T. Mizuno, “A Meta-Data-Based Data Aggregation Scheme in Clustering Wireless Sensor Networks,” *MDM’06*, 2006.

[8] C. Dugas, “Configuring and managing a large-scale monitoring network: solving real world challenges for ultra-lowpowered and long-range wireless mesh networks,” *Int. J. Network Mgmt*, 2005, vol 15, pp. 269282.

[9] H. Zhou, L. Ni, M. Mutka, “Prophet address allocation for large scale MANETs,” *IEEE INFOCOM*, April 2003, USA.

[10] C. Prehofer, C. Bettstetter, “Self-organization in communication networks: principales and design paradigm,” *IEEE Communications Magazine*, vol 43, no 7, pp. 78-85, July 2005.

[11] J.-L. Lu, F. Valois, D. Barhel, “Low-Energy Self-Organization Scheme for Wireless Ad Hoc Sensor Network,” *IEEE WONS*, January 2007, to be published.

[12] L. Samper, F. Maraninchi, L. Mounier, E. Jahier, P. Raymond, “On the Importance of Modeling the Environment when Analyzing Sensor Networks,” *IEEE IWWAN 2006*, New York City, USA, June 2006.

[13] F. Ghenassia, *Transaction Level Modeling With SystemC: TLM Concepts And Applications for Embedded Systems*, Springer-Verlag, 2005.

[14] A.J. Martin, “The Limitations to Delay-Insensitivity in Asynchronous Circuits”, in *Advanced Research in VLSI*, W.J. Dally, Editor. 1990, MIT Press. pp. 263-278.

[15] T. Pering, T. Burd, R. Broderesen, “Dynamic Voltage Scaling and the Design of a Low-Power Microprocessor System,” *Proceedings of the Power-Driven Microarchitecture Workshop*, 1998, pp.107-112.

[16] D. Rios-Arambula, A. Buhrig, G. Sicard, M. Renaudin, “On the use of Feedback Systems to Dynamically Control the Supply Voltage of Low-Power Circuits”, *J. Low Power Electronics*, vol 2, 2006, pp. 45-55.

[17] F. Bouesse, M. Renaudin, A. Witon, F. Germain, “A Clockless low-voltage AES crypto-processor,” *European Solid-State Circuits Conference (ESSCIRC 2005)*, Grenoble, France, September, 12th - 16th, 2005, pp. 403-406.